

USE OF A GAS UNDER VARIABLE PRESSURE TO CONTROL
REACTIVITY IN POWER REACTORS

N.LAGRANGE, L.DOLLE, J.P.SATRE, G.DIRIAN

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USE OF A GAS UNDER VARIABLE PRESSURE TO CONTROL REACTIVITY IN POWER REACTORS*

M. LAGRANGE, L. DOLLE, J.P. SATRE, and G. DIRIAN
(Commissariat of Atomic Energy, Paris, France)

A. IDEA OF THE GASEOUS CONTROL BANK

I. Introduction

Among the first ~~works~~ relative to the chemical control of nuclear reactors by elements ~~with high~~-neutron capture cross-section introduced in the dilute form in the core, two procedures of putting it into play are apparent for reactors with liquid moderators:

1. The placing in solution of a compound of the absorbing element in the moderator leading to long response times but which does not require the addition of a supplementary circuit to the reactor vessel, the existing purification circuits being sufficient.
2. The introduction of this compound or a solution of it in a special independent circuit transversing the core which enables us to obtain shorter response times owing to the reduced volume of material to be treated.

Already, at this time, the idea of employing an absorbing element in gaseous form is equally investigatable. There exists a certain number of gaseous boron compounds, the utilization of which seems especially more advantageous as the availability of boron enriched in the isotope B^{10} becomes generalized. Another element, helium 3, although more difficult to supply, has already been equally recommended (see references 1 and 2).

But if, in principle, the placing of a homogeneous solution of the gas in the moderator and its progressive elimination by degassing are possible, this technique is nevertheless eliminated a priori. In effect, there exist reasons of a chemical nature like the hydrolysis of boron compounds with the products which it carries along, or physical like the solubility of the gases, the conditions of stability of the solution with variations of temperature and the hydrodynamic regimes in the reactor vessel and associated circuits which excluded almost totally. Therefore, the control of reactivity by an absorbing gas can only be done with security with the help of an auxiliary circuit which submerges in the core and isolates the gas from the moderator. The variation of control strength of such

*Translated by Colin A. Heath, NASA Lewis Research Center, Cleveland, Ohio, presently employed by General Atomics, San Diego, Cal.

a gaseous bank is obtained by modification of the mass of absorbing gas contained in that part of the circuit which is located in the core. Several of these banks repeated over again in the core could be parallel branches of the same command circuit exterior to the reactor.

II. Definition of the procedure of using an absorbing gas in a gaseous bank

1. Principle

The control strength of a gas contained in a tube situated in the core of the reactor is proportional to its pressure or eventually to its partial pressure if it is diluted in an inert gas or carrier (more on this later). As a result of the consumption of the absorbing gas by neutronic reactions, a slow but quasi-permanent fission of gas is necessary. The element which results from the neutronic consumption of the absorbing gas is generally an inert diluent or even undesirable for chemical reasons. There is every reason to evacuate it, periodically or in a continuous fashion depending upon the case. For reasons of convenience, it is preferable then to circulate the gas in a circuit which traverses the core, or better yet, in a hairpin shape permitting the grouping of the system on a single face of the reactor. One such circuit is schematically represented on figure 1.

The variation in control strength follows from the order given by the action of electric valves of which the one promotes the loss of gas from the bank into a reservoir of low pressure, and the other an introduction of supplementary gas by leaving a reservoir of high pressure. A single transfer pump maintains the pressure of the low-pressure reservoir below that which exists in the control bank and makes up the gas in the reservoir of high pressure. The latter is provided in case of a need of a reserve of absorbing gas. An appropriate purification device is placed directly at the head of the bank. The circulation of gas in the bank and the purification device is assured by a blower of low yield.

2. Properties of the procedure of control by gaseous bank

Virtues and advantages of a control device for reactivity by the variation of the quantity of an absorbing gas in the circuit of a gaseous bank.

at strength as is
By the same standard with which a poison distributed weak concentration in a homogeneous fashion in the moderator, a gas introduced in a circuit which traverses the core is generally ~~gray~~ to thermal neutrons. It possesses an effectiveness ~~sensibly~~ ^{practically} constant in the part of the core which the circuit occupies. From this point of view, a gaseous bank is less uniformly effective ~~than~~ ^{than} a poison ~~solution~~ ^{ous} in the moderator, but in comparison with solid elements which are black to neutrons on that part which enters in the core, the distortions in the flux are very weak.

For these reasons, it is easy to choose conditions of operation such that the control strength of a gaseous bank remains approximately proportional to the pressure of the gas or to its partial pressure in a mixture with an inert diluent.

Moreover, if judiciously arranged, a collection of such gaseous banks will serve simultaneously to flatten the neutron flux in the core.

As the capacity of an independent circuit including the bank itself and the means of command is very much reduced, the means of purification of reconcentration or addition necessary to be placed in the system are also of small dimensions. The quantity of poison itself is reduced and the purifications are able to be performed without appreciable loss, except with recuperation or regeneration. The effective consumption of the poison is nevertheless important.

Finally, an independent system of small volume is likely to respond rapidly to demands of the variation of control strength.

3. Choice of an absorbing gas

The number of gaseous compounds or elements with sufficiently high capture cross section is in reality reduced. Only a few compounds of boron listed in table I and helium 3 offer themselves as a choice. It is recognized nevertheless that among them, boron trifluoride alone would possess the required physical properties and simultaneously a sufficient chemical stability. Still, it would be necessary to exclude completely its contact with water (for example, in the case of a leak toward the inside of the reactor vessel). In contrast, helium 3 possesses a collection of properties which make it from all points of view useful in the utilization of a gaseous control bank, taking equally into account the simple and easy procedures of purification which it is possible to place in the system. In the system of gaseous banks of the reactor of EL 4, it has been decided therefore to employ this gas at low pressure. If the effective absorption cross section of the gas is sufficient in order to permit its use at low pressures, a rupture of the circuit perturbs slowly the control strength of the bank.

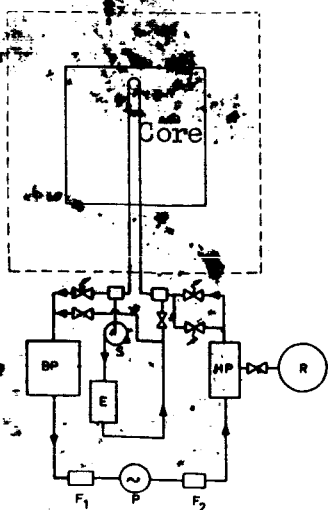


Figure 1 - Schematic of the principal parts of a gaseous bank.

- S : Electric valve
- BP : Low pressure reservoir
- HP : High pressure reservoir
- P : Pump
- R : Reserve of gas
- S : Blower
- E : Purification device
- F1 : Dust filter
- F2 : Oil filter

Table I

COMPOUNDS WITH SUFFICIENTLY HIGH CAPTURE CROSS SECTION

Compound	Density	Melting point (°C)	Boiling point (°C)	s_a (mm ² /g)	Σ_a (cm ⁻¹)	Observations
BF_3	2.99 g/l	-127	- 101	592	0.018	- Hydrolizes with heat in water into HBO_2 + hydrogen fluoride.
10BF_3	--	-	-	3,210	0.096	-
BCl_3	1.434 (0°C)	-107	+ 12	367	-	- Hydrolizes in water into HBO_2 and hydrochloric acid.
B_2H_6	0.1447 (-112°C)	-165	- 92	2960	-	- Hydrolizes in water into HBO_2 and hydrogen unstable in the gaseous form.
B_4H_{10}	0.59 (-70°C)	-120	+ 18	3000	-	- Hydrolizes in water into HBO_2 and hydrogen unstable in the gaseous form.
$\text{B}_2\text{H}_5\text{Cl}$	-	-	- 78 (18 mm)	1320	-	- Very unstable.
$\text{B}_2\text{H}_5\text{Br}$	-	-104	+ 10	740	-	- Hydrolizes in water into HBO_2 + HBr + H_2 .
3He	0.1339 g/l	-	-	89,000	0.120	- Inert gas.

$s_a = \frac{60.24 \sigma_a}{\alpha A}$: effective absorption cross section in square millimeters per gram for pile neutrons
 α = a correction factor taking into account the maxwellian distribution of pile neutrons;
 for effective cross sections with $1/v$; $\alpha = 1.128$.

$\Sigma_a = \frac{ds_a}{100}$: effective absorption cross section per cubic centimeter in inverse centimeters for pile neutrons; d = density

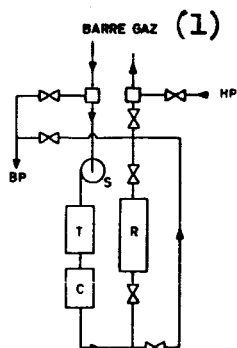


Figure 2. Schematic of the Principle Parts of the Purification Device for a Gaseous Bank

Key: 1 - gaseous bank
 S - blower
 T - separator
 C - concentrator
 R - regenerator

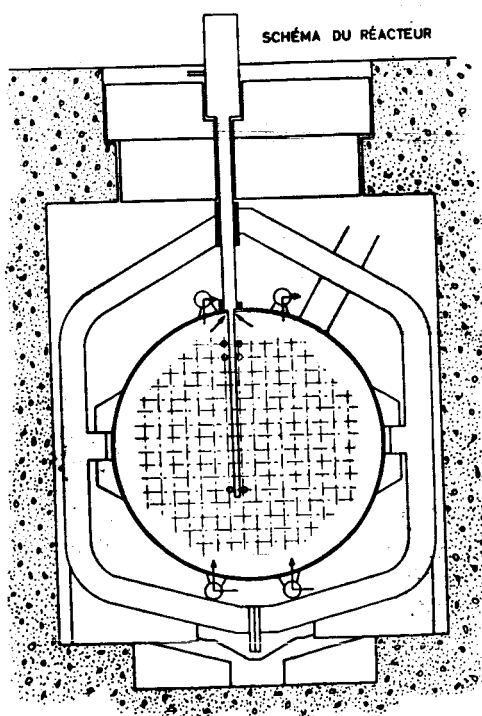


Figure 3. Schematic of the Reactor

4. Conservation of effectiveness

Elimination of impurities produced by the reaction of neutronic capture

The products of the capture reaction of thermal neutrons by helium 3 are tritium and hydrogen produced in equal quantities : a rate proportional to the neutron flux in which the bank is immersed. Purification consists of eliminating these two gases, chemically reactive, from the inert helium 3, then the recovery of the tritium. This latter will be able to be used either as such or to permit by decay the regeneration of the helium 3 consumed. In principle, if one does not take into account the inevitable losses due to leaks in the course of manipulation, a gaseous bank of helium 3 should be able then to maintain itself more or less the same according to the quantity of tritium accumulated during the preliminary functioning. Figure 2 represents schematically a purification circuit designed to separate and to settle the hydrogen gas and tritium.

Different methods of separation are possible.*

- (a) the diffusion at an appropriate temperature across a barrier made up of palladium or an alloy of palladium and silver.
- (b) adsorption on the palladium.
- (c) chemical fixation under the form of a metallic hydride.
- (d) catalytic combustion or in the presence of a metal oxide easily reduced.

Without going into the details of the respective merits of these methods, it is recognized that the formation of hydride and combustion deliver at low cost and in a single phase hydrogen and tritium in a form very condensed or easily condensable. However, hydrides present certain dangers which make them prefer the formation of water by combustion. The latter is then fixed in the concentrator by reversible absorption on a bed of desiccant such as silica gel or an easily regenerated molecular screen. Finally, if the tritium is destined for the restrengthening of the gaseous bank by helium 3 from decay, it is possible to transfer the water at the moment of the recuperation of the concentrator into a regenerator in order to fix it chemically on an absorbant of very great capacity such as phosphoric anhydride capable of committing to be liberated subsequently only the helium 3.

Finally, the direct transformation of the hydrogen and the tritium into water by radiolytic reaction under the effect of ionizing radiation and from recoil atoms in the reactor can be envisaged; the gas will then be supplemented with oxygen or a donor of oxygen. A circuit of gaseous banks using helium 3 diluted with oxygen has been proposed before (see reference 3). One knows that under the effect of β radiation the tritium is oxidized in oxygen and traces of humidity accelerate the reaction (see reference 4). The yields of the same reaction under the effect of recoil atoms of tritium and of nascent protons in the reaction of neutronic capture

* Studies relative to different modes of separation are pursued in the Laboratories of C.E.A. by P. Vignet.

are actually studied in the reactors of Saclay in view of knowing the advantages that it perhaps would offer.

B. APPLICATION TO THE REACTOR EL 4

I. The reactor EL 4

1. General characteristics

The reactor EL 4 constitutes the heat generator for the central electric power station in construction in the mountains of Arrée in Brittany.

Its power is 240 MW(t) for 78 MW(e).

This reactor is the prototype of a series of reactors for power having as moderator heavy water, as fuel natural uranium, and as coolant carbon dioxide under the pressure of 6×10^5 pascals (one pascal equals one newton per meter squared).

2. Dimensional definitions

The core of the reactor is composed essentially of a cylindrical vessel with horizontal axis of 4.8 meters in diameter and 4.6 meters in length. This vessel is equipped with 216 horizontal ducts called pressure tubes, which are distributed in a square array having a characteristic dimension of 234 millimeters, the total envelope circumscribed forming an octogen. These ducts which have external diameter of 113 millimeters receive the internal equipment destined to support the fuel, and serve as conduits for the cooling gas. This assembly is placed on the inside of thermal baffle plates of the cell of the reactor shield consisting of a cavity of construction-grade concrete which contributes to the biological protection.

Above this, and in the vertical axis of the vessel, is found the tubular block which contains the biological protection at the top while leaving a passage to the cavity filled with the control mechanisms and measuring systems. It is formed by a cylinder of 4.5 meters in diameter and 3.4 meters in height filled with concrete.

The control banks penetrating to the interior of the core must therefore be inserted in the intervals between the pressure tubes. They are as a consequence repeated in the vertical plane at distances which are a multiple of 234 millimeters. Their distribution in the radial plane is symmetric in such a fashion as not to perturb the distribution of the flux in the core.

3. Neutronic definitions

The means of control must permit:

- (a) the compensation of variations in reactivity,
- (b) the control of neutron power
- (c) respect of the safety conditions in startup and shutdown

The reactor charged with new natural uranium at normal operating conditions totals up the following control worths with respect to the cold condition. The table that follows contains the unit of reactivity, pcm. (As far as can be determined, this abbreviation means millipercents or $\% \times 10^{-3}$.)

Effect of temperature	:	1800 pcm (moderator and fuel)
Xenon poisoning	:	2800 pcm
Margin of reactivity	:	500 pcm
Margin of control worth:	:	100 pcm
Fine control	:	100 pcm
Samarium effect	:	<u>600 pcm</u>

total : 5900 pcm

The uncertainty which is connected with these values and the imprecision of the calculations of control worth make for a margin of safety which will be conservative in the effect on the means of control.

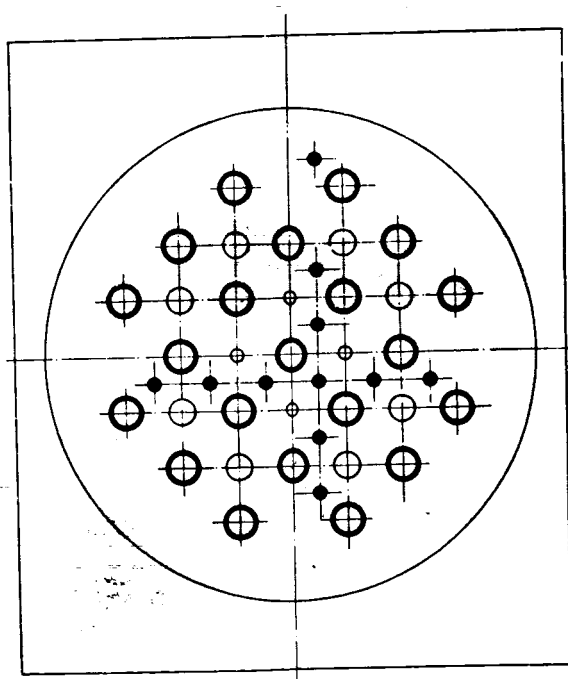


Figure 4

EL 4. General deployment of the assembly of banks

- : Bank of safety compensation
- : Bank for mechanical fine control
- ⊙: Bank for gas compensation
- : Hoist for flux measurement

II. Control banks

1. Solutions of the advanced design

a. Mechanical solutions

The advanced design drawn up in December of 1960 by the Society INDATOM in the capacity of industrial architect in the construction of the reactor contained: 17 banks of safety compensation, 4 banks for eventual holddown, and 8 banks of fine control.

All these banks were driven by classical mechanisms. The banks for safety compensation are a cable winch and the banks of fine control by a pinion gear assembly.

b. Other possible solutions

The control of the safety compensation banks could still have been provided by a strip or chain winch. Control of the fine control banks could have been provided by a chain winch or with the aid of a binding-post assembly. The two systems could have been driven by hydraulic screw-jacks.

c. Advantages and disadvantages

The advantage of mechanical solutions resides in the fact these are systems which have already been proven in other reactors, although in the case of EL 4 the loads or the velocities are different.

Some changes in technological points will probably be necessary in order to assure a certain safety of operation.

The disadvantages are of several types:

Neutronic: All these mechanical banks penetrate into the core from a single lateral face, creating an asymmetry in the corrective action by distortion of the flux.

No corrective action is possible during the course of operation unless by the pure and simple replacement of the absorbing element.

Mechanical: Presence of mechanisms in the heavy water requiring the use of special materials. Difficult accessibility in the case of intervention due to the presence of blocked passages. Wear of mechanisms in movement.

Dimensional: Situation of winches and motors in the head of the bank involves an obstruction on the head of the tubular block.

Biological protection not assured by the screw-jacks in case of a drop of the level of the heavy water in the reactor vessel which would have the effect of emptying the driving cylinders.

2. Solutions proposed in the course of the study

The discriminations of the functions result from studies performed since the time of the advanced design by the construction group of Delle which have permitted the effective division of the three functions:

Safety: by classic mechanical banks with control by a cable winch.

These black absorbing elements are outside of the core when the power reaches $0.7 P_{\max}$ and only come into play as a slow removal from the startup of the reactor in order to assure the compensation of important variations in reactivity:

Effect of temperature	: 1640 pcm (millipercents, representing 160° C to 1800° C)
Safety margin	: 1000 pcm
Xenon effect	: <u>2710 pcm</u>
Total	5350 pcm

The other time in which these banks come into play is by rapid insertion in case of a scram or an incident.

These gross safety banks are 21 in number.

Compensation: Eight banks assure this function in order to adjust variations of reactivity during power operation. These variations are slow (in the order of 10 pcm per second) but of great amplitude, i.e., 20 pcm every 2 seconds.

These banks come into play when the power reaches 0.7 of maximum and permit the readjustment of the fine control banks at their maximum level of effectiveness.

Compensation of transients:	600 pcm
Compensation for the residual of temperature effect	: 160 pcm
Addition of 90 pcm (remainder of the xenon effect)	: <u>90 pcm</u>
Total	850 pcm

These banks participate equally in the safety function.

Fine control: Fine control of neutron power is assured by two groups of two banks, two being in reserve outside of the core.

Their action has the effect of adjusting the power to the value consigned by variations of rapid effectiveness (30 pcm per second) and of minor amplitude, the total effect of a bank being 50 pcm.

These banks are in service no matter what the level of the power.

III. Study of gaseous banks

1. Fundamental conditions of applicability

The scheme of principle adopted is very simple. The difficulties of realization are due essentially to the following requirements: (a) obtaining a high value of the ratio of the maximum control worth of the bank to the minimum control worth of the bank in order not to permanently burden the neutronic economy in the reactor; (b) to obtain an almost constant rate in variation in reactivity whatever may be the exit pressure in the bank; (c) to effect in excellent gas tightness upstream and downstream of the electric valves situated between the reservoirs and the banks otherwise the bank risks becoming the principle source of perturbations of reactivity in the reactor; (d) to effect an almost perfect leak tightness for the circuit with respect to the exterior, taking into account the high price of the fluid which it will contain; (e) to preserve the air tightness in the case of a failure of a part of the circuit; any false maneuver putting the circuit in connection with the atmosphere must be practically impossible; (f) to guarantee the strength of all the elementary materials mounted in the circuit so that disassembly for a revision or a replacement of parts would have a practically zero probability once the circuit was filled with absorbing gas.

The conditions stated above have led to consideration of a technological study well advanced towards the design stage. All the problems are still not resolved at this actual time but the necessary means of study and of analysis are in place.

2. Requirements of operation

They are the following: (a) the maximum pressure employed in the gas must be near the atmospheric pressure in order to avoid the risks of leakage to the exterior; (b) the investment in helium 3 must be as small as possible compatible with accomplishing required performance; (c) the endurance of the means of control must be sufficient to limit interventions in time [Note: that was the literal translation; it probably means in order to limit shutdowns]; (d) in order to limit the residual control worth of the bank, the ratio of maximum to minimum reactivity worths should be large (>15).

Without entering into the detail of the technical studies already done, or in progress, we will simply indicate a few studies particularly connected to these conditions. The complete design schematic for the system of two groups of banks is represented in figure 16 which will be discussed later.

3. Mode of action

The variation in reactivity is obtained by a change in the mass of the gas contained in an enclosure placed in the interior of the multiplying medium. The variation of the mass would be able to be obtained either by a variation of

***TRANSLATOR'S NOTE**

the pressure of the single gas helium 3, or by variable dilution at constant pressure with an inert gas, or by variation of the pressure of a mixture of two gases.

a. Resulting requirements

Neutronic requirements: Requirements connected to the conditions (a) and (b); the maximum allowable value of residual control worth is of 130 millipercents for a system of 8 banks. Taking into account the absorption due to the structures of Zircaloy, the minimum pressure of helium 3 in the bank is of the order of 0.06 bars; the low pressure reservoir is therefore maintained at a pressure less than about 0.04 bars. The maximum pressure in the bank is about 0.64 bars.

Interactions between the bank and the two reservoirs will be accomplished by the use of electric valves and orifices. Taking into account the scale of the variations of pressure in the bank, it is necessary to divide by two the number of orifices if one wishes to obtain the greatest part of the scale the maximum speed of 30 pcm per second and without going below the minimum value of 10 pcm per second. This leads in the same way to cutting in half the number of electric valves therefore to the increase of the standard of air tightness above and below these installations.

Mechanical requirements: Requirements related to conditions (c) and (d); the gas seal with respect to the exterior has been obtained by limiting the number of connections. It is planned that only the following subassemblies will be connected to the circuit by breakable connections. Each bank, the cell of purified tritium, the different pumps, the filters, and the reserve reservoir. In contrast, all the little material (electric valves, stopcocks, diaphragms, sample collectors) is joined by inert gas welding.

4. Advantages and disadvantages of the procedure

Advantages

(a) neutronic. (a) constant effectiveness on the whole length of the bank inside the multiplying medium; (b) the ease with which during the course of operation one is able to change the effectiveness of the bank by adding to the absorbing helium 3 a neutral gas of the same characteristics, for example, helium 4.

(b) mechanical. The pieces situated in the core are static. The only requirement being the gas seal; moreover no moving parts would be in contact with the heavy water. All the mechanisms are located in a place in the room with the gas banks. They are by consequence accessible and easily replaced.

(c) dimensional. The dimensions of the effective circuit are very restrictive. The volume of the head of the bank is limited by the connecting flanges of the inlet pipes of the gas. The reduced congestion with the bank permits limiting the investment in heavy water by reducing the volume crossing the tubular block.

Inconveniences or disadvantages

It is necessary to eliminate the products resulting from the neutronic reaction on an absorbent in order to conserve the effectiveness of the bank and to maintain the quantity of new gas necessary for operation.

The making of a gas-tight circuit crossing the reactor core leads to a slender form and therefore a fragile one, at least during the time of manipulating the thing either into or out of the core.

5. Exploration of applicable procedures

The ambition of those responsible for the studies was at first to adopt the system of gaseous banks to the fine control function but with high performances and from this capability followed the compensation function. That is to say, to the replacement of all the correction elements that are present in the core at nominal power.

The examination of systems to place in the circuit has oriented the researchers in two principal directions: the circulation systems and the volumetric systems:

(a) Circulation systems

Circulation in the bank.

Absorbing gas only at variable pressure.

For reasons of security seeking to avoid the piercing of the moderator vessel in the bottom part, the solution of a tube crossing from one side to the other has been rejected. It prohibited any simple replacement in case of an incident.

The possible solution remained the bank shaped like a hairpin or for the two coaxial tubes permitting the entrance and exit from the same side of the reactor. The corresponding scheme is that shown in figures 5a and 5b.

A pump assures the regular transfer of gas from a low-pressure reservoir toward a high-pressure reservoir, the bank being placed in series between the two reservoirs. In order to limit the rapid loss of control strength, an orifice on the low-pressure side is necessary, the regulation being obtained by using an adjustable valve at the entrance to the bank.

In order to simplify the control, the orifice on the downstream side should be of a constant cross section.

In the case of using pure helium 3 gas, some difficulties became evident when it was a question of defining the relative cross sections between the valve and the orifice, taking into account the limitation on the speed on the variation of reactivity at 30 pcm per second. The two sections being different by only a very small amount (0.1 mm^2), this arrangement practically imposes an independent circuit for each bank.

Furthermore, for small values of variation of reactivity, the change of the cross section of the valve leads to a precision positioning that is practically impossible. In effect, for variations on the order of 5 pcm,

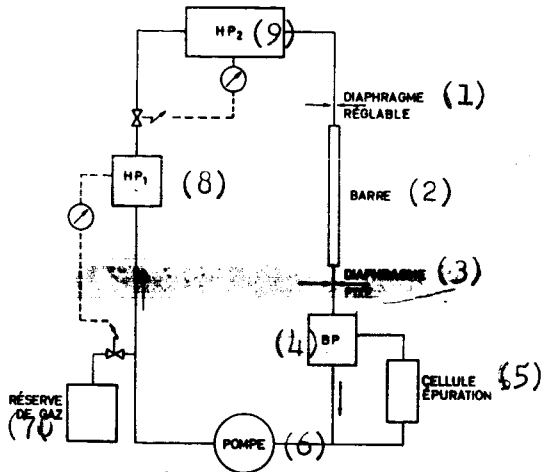


Figure 5a. Solution to Circulation
With Two Reservoirs

- Key:
- 1 - regular orifice
 - 2 - bank
 - 3 - fixed orifice
 - 4 - low pressure reservoir
 - 5 - purification unit
 - 6 - pump
 - 7 - gas reserve
 - 8 - high pressure reservoir 1
 - 9 - high pressure reservoir 2

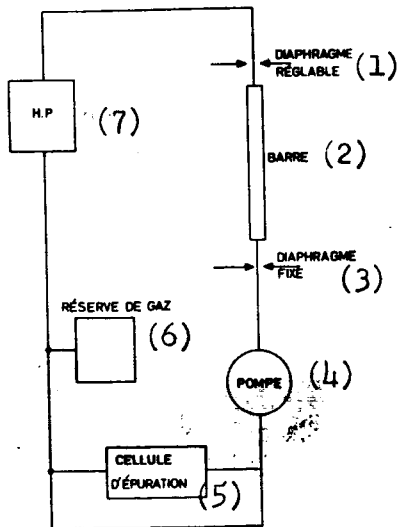


Figure 5b. Solution to Circulation
With One Reservoir

- Key:
- 1 - regular orifice
 - 2 - bank
 - 3 - fixed orifice
 - 4 - pump
 - 5 - purification unit
 - 6 - gas reserve
 - 7 - high pressure reservoir

the variation of the orifice at the entrance will have to be on the order of 10 parts per 100 for a diameter of 0.7 mm.

A circuit with constant pressure and with variable dilution.

In order to free ourselves from these restrictions in the realization of the mechanical powers, it has therefore been proposed to use a mixture of helium 3 with an inert gas more dense (CO_2). But apart from the delicate problem which is posed by the separation and purification of two gases by liquefaction at -80°C at atmospheric pressure, a difficulty continues to exist in the regulation in the supply of helium for low values leading us back practically to the preceding degree of impossibility.

A circuit with constant dilution and with variable pressure.

By operating, for example, with 1 volume of CO_2 for 1 volume of helium 3, the volumetric mass being increased as opposed to that which exists for an absorbing gas alone, the sizes of the orifices will be able to be larger and will reach acceptable values.

This arrangement has, however, a disadvantage of an increase of flow rate which reaches 360 cubic meters an hour (being 100 liters per second) for a speed of circulation of 6.5 meters per second, involving the use of prohibitive amounts of power.

Moreover, it is to be feared that the mixture of gas would not be homogeneous in the bank.

In conclusion of the study of circulation systems in the bank, one is able to state that in the three cases envisioned, no single solution gave satisfaction. The speeds of variation in pcm are limited either by conditions of mechanical execution difficult to realize, or by placing into the circuit machines involving large investments and considerable operating expenses.

Circulation exterior to the bank.

Discharge into a tuyere.

The circuit proposed (fig. 6) is independent of the bank itself. In order to obtain rapid changes with precise small amplitude, it has been conceived to join the volume of the bank to a chamber which makes up the casing of a supersonic blast pipe (fig. 7).

The pressure which exists in this chamber is a function of the position of the needle in the neck of the blast pipe.

The regulation is precise. The velocity in the blast pipe being supersonic, the response times will be short and the pressure in the blast pipe will be able to be varied in the ratio 1 to 20.

The frequency of controls will be able to be great since the establishment of the pressure of the air intake is practically instantaneous.

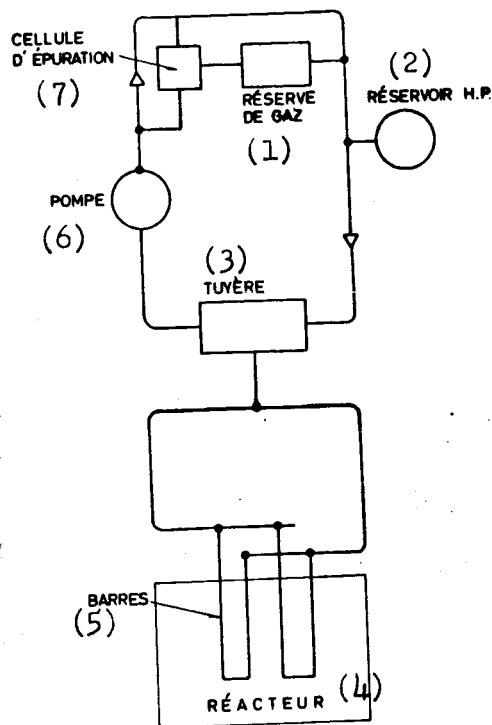


Figure 6. Solution to Circulation with a Tuyere

- Key:
- 1 - gas reserve
 - 2 - high pressure reservoir
 - 3 - tuyere
 - 4 - reactor
 - 5 - banks
 - 6 - pump
 - 7 - purification unit

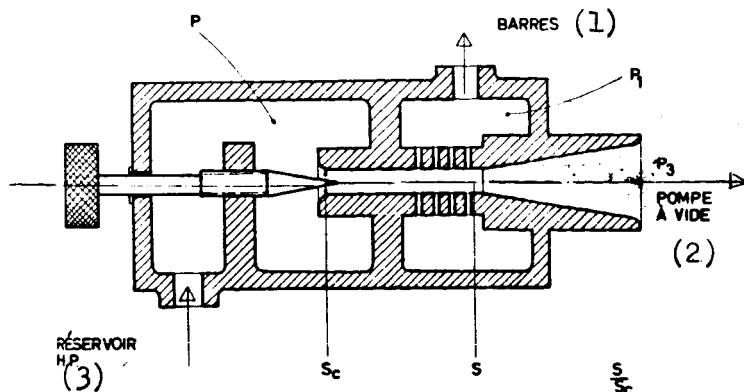


Figure 7. Solution to Circulation with a Tuyere

- Key:
- 1 - banks
 - 2 - vacuum pump
 - 3 - high pressure reservoir

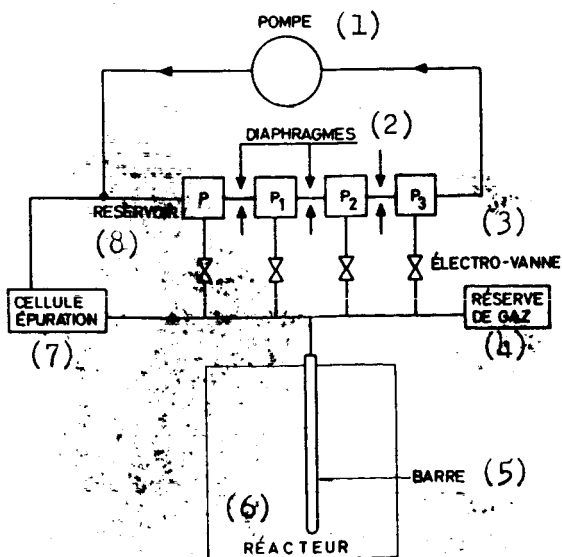


Figure 8. Solution to Circulation with a Loss in Pressure

- Key:
- 1 - pump
 - 2 - orifices
 - 3 - electric valve
 - 4 - gas reserve
 - 5 - bank
 - 6 - reactor
 - 7 - purification unit
 - 8 - reservoir

The supply is still large (400 m^3 per hour) and the system demands the permanent operation of pumps for a small part of the supply is directed into the bank from whence results still a speed of variation in control limited in pcm.

This system has the advantage of permitting the supply of several banks in parallel contrary to the design with an orifice.

It is indispensable for the reasons of the stability of the flow not to lower the speed of the gas below a Mach number of 1.1.

Flow rate at a loss in pressure.

A design for gas flow is represented in figure 8 accounting for very great losses in pressure spread out between maximum pressure and minimum pressure. The pressure valves are placed all along this tube and are connected to the banks through the intermediate electric valves. The advantage of this system is that it is extremely rapid and enduring. The loss of a large pressure in the tube will send all the supply into the banks. The valves will be able to allow a leak. The disadvantage of the system is then still the necessity of the continuous operation of the pump and, furthermore, to furnish the quantum of variation in pressure which one could only reduce by increasing the number of expansion cells and, accordingly, multiplying the number of valves.

Mass plugs are arranged between each stage in order to help the operation of the system.

The supply remains very high (520 m^3 per hour equals 150 liters per second).

In resume, the solutions envisioned with the object of fine control lead either to very large difficulties in fabrication or fine adjustment or to the placing into the system of materials requiring very high power. It has therefore been anticipated to limit in the first state the application of gaseous banks to the sole function of compensation, realizable with systems of the volumetric type.

(b) Volumetric systems

Control of variations of pressure with deformable membranes in metal or plastic bellows (fig. 9).

Metal bellows do not allow the conservation of a ratio lower than the value 15 desirable between the maximum and minimum pressures. Only plastic bellows permit such a variation but a difficulty remains in the diffusion of helium through plastic material.

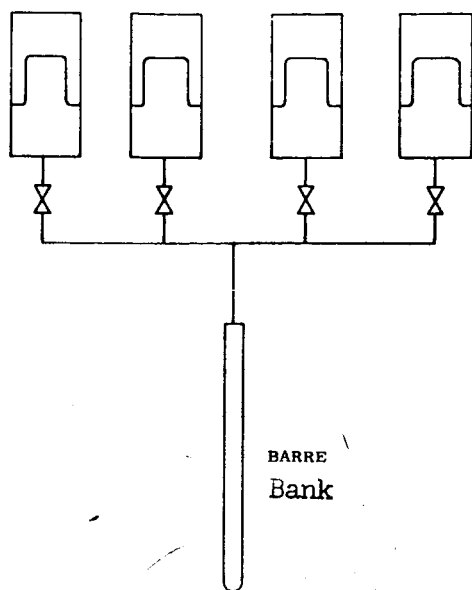


Figure 9. Volumetric Solution with Membranes

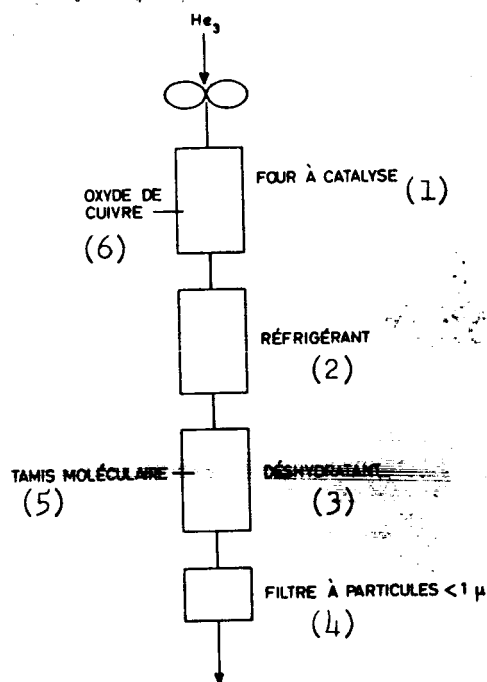


Figure 11. Purification Circuit

- Key: 1 - catalytic furnace
 2 - refrigerant
 3 - dehydration unit
 4 - particulate filter
 5 - molecular sieve
 6 - copper oxide

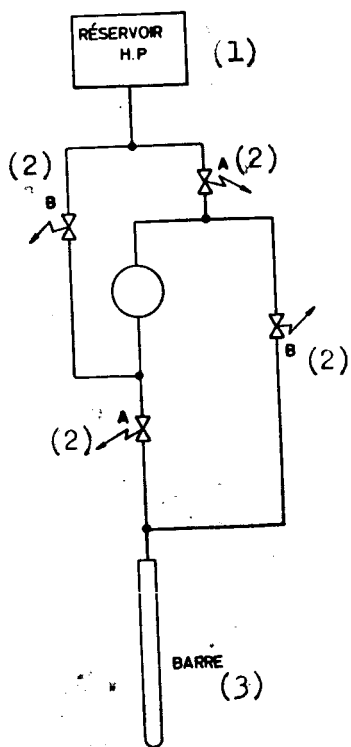


Figure 10. Volumetric Solution with a Reservoir

- Key: 1 - High pressure reservoir
 2 - electric valves
 3 - bank

These bellows perform the work at the same time as the pump and the reservoirs of the preceding system. In order to obtain the ratio of pressures desired, the membranes are voluminous and numerous. Being voluminous, taking into account the value of the pressures, the force exerted on the membrane will be large leading to a heavy mechanism involving a considerable obstruction.

The system of control will be able to act on all the membranes simultaneously but the ratio of velocities of displacement of the membranes will reach 200 depending on whether the action takes place at low pressures or high pressures in order to conserve the desired speed in the variation of control worth which involves another obstacle.

Another method of realization would consist of controlling the membrane successively permitting in this way the reduction of the number and reducing the ratio of the speeds of displacement. The disadvantage of requiring gas-tight valves between the circuits, however, appears.

Constant volume system with a pump and a reservoir.

The schematic is presented in figure 10.

Each circuit of a bank is independent. In order to assure a constant speed of variation of reactivity, the flow of the pump is variable if one considers the moment of the end of the discharge or the refilling where it is low. The exchange of the mass of gas occurs between the bank and the reservoir.

Volumetric system with a pump and two reservoirs.

The schematic is represented in figure 16. Two reservoirs are arranged: one at low pressure, the other at high pressure connected by the pump. The high pressure reservoir will be able to contain the entire mass of the gas. The electric valves will connect each of the two reservoirs to the distribution circuit of the banks. The electric valves should be gastight.

The speed in the variation in millipercents is proportional to the pressure in the bank. The amount of time that the electric valves are open is therefore a function of this pressure.

The pump is at low flow and connects a group of banks. Its intermittent operation is controlled by the pressure of the low pressure reservoir.

Some orifices are necessary in order to limit the speed of the flow of the gas. The regulation of the variations in reactivity will be affected by the duration of the opening time of the electric valves.

One operates here with quantum jumps of 25 pcm which correspond to the maximum tolerable amplitude for fine control banks.

6. Solution chosen

(a) Application to the compensation function

The last description is the most favorable if one considers the per-

performances obtained, the low power for the pump, its intermittent operation, the flexibility of operation which permits, by a simple manipulation of valves, operating on one or on several banks simultaneously.

The ensemble of installation will be made up, therefore, of 8 banks of compensation divided into two identical groups each commanded by a pumping system.

The instantaneous speed of the variation of pressure of a group will be limited to 30 millipercents per second, the median speed being reduced to 10 millipercents per second by delaying between two jumps in reactivity.

(b) Extension to the safety function

It has appeared easy to use the gaseous banks in the safety function. In effect, independently of the circuits described, the addition of a particular circuit with a large cross section (1 cm^2) between the high pressure reservoir and the banks permitting the rapid introduction of the absorbing gas.

The general control of the reactor commands the aforementioned safety electric valve which results in a contribution of control worth of 400 millipercents in one-tenth of a second.

Naturally, the safety valve for safety reasons is permanently energized and opens with a loss of power. With the normal operating compensation circuits, it is possible to remove about 300 pcm at 30 pcm per second following a safety shutdown.

(c) Consumption of an absorbing gas

For a reactivity assembly of 800 millipercents, the reactor contains 1.6 grams of helium 3.

The quantity of neutrons absorbed at the nominal power of the reactor will be: 0.63×10^{17} neutrons per second.

The number of atoms of helium 3 destroyed each day is therefore 0.55×10^{22} or 1.1 per 100 of the initial 1.6 grams. This will be 6 grams per year.

The replenishment of helium 3 can be accomplished periodically after static measurements of pressure in the circuits which permit the calculations of gas consumed. The replacement is controlled by measuring the increase of the pressure in the low pressure reservoir following the introduction of new helium 3 flowing from a reserve reservoir.

The operation will be able to be accomplished manually, being fairly infrequent (one time per month).

Between two replenishments, the effective loss of gas is automatically compensated by the fine control banks since the time between recharging corresponds to a loss of control strength of about 20 pcm.

(d) Coefficient of temperature of a gaseous bank

The variable pressure circuit containing the bank and limited by the

electric valves for refilling and for discharge is composed of two parts: the part effectively with volume V_1 is at the temperature T_1 of the moderator, and the external part ~~xxx~~ outside of the reactor of volume V_2 is at the exterior ambient temperature T_2 .

All the electric valves are closed, the mass M of helium contained in the circuit is constant and is reported at a mass m_1 in the volume V_1 and m_2 in the volume V_2 .

A variation of the temperature dT_1 of the moderator leads to a variation dm_1 of the effective mass responsible for a variation of reactivity. In the same way, for a variation dT_2 of the external temperature one obtains a variation dm_2 of the exterior mass.

One is therefore able to define two coefficients in temperature of the gaseous bank:

α_1 ~ coefficient of internal temperature

α_2 ~ coefficient of external temperature

A simple calculation shows that $\alpha_1 = \frac{d\rho}{dt} = -\frac{\rho_1}{T_1} \left(\frac{1}{1+V_1/V_2} \right)$

ρ_1 - the control strength of the bank in pcm.

$$\alpha_2 = \frac{d\rho}{dt} = +\rho_1$$

One sees that one desires to reduce the volume V_2 with respect to V_1 in order to diminish the coefficient α_1 . Furthermore, this is compatible with a minimum investment of gas. In the particular case of the reactor EL 4, one arrives at:

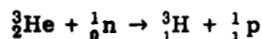
$$\alpha_1 = -2 \text{ pcm} \cdot ^\circ\text{C}^{-1} \times \rho_1 / 850$$

$$\alpha_2 = 2 \text{ pcm} \cdot ^\circ\text{C}^{-1} \times \rho_1 / 850.$$

These values are very acceptable taking into account the fact that the variations of temperature are slow and of minor amplitude. It would be difficult by contrast to use this means of control in the opposite case.

(e) Elimination of the products of transformation (fig. 11)

Helium 3 gas absorbs thermal neutrons following the reaction :



The bank forms a finger of a glove. It is therefore important to connect to this upper part a pipe network for drawing off gas functioning in a closed circuit and containing a blower to conduct the gas into a catalytic furnace which contains copper oxide where the tritium and the hydrogen are oxidized. The water formed is cooled in a refrigerant before entering

a dehydrating part containing silica gel or a molecular screen which recovers the water and the tritium oxide. Finally, the gas thus purified crosses a particulate filter before being reintroduced into the circuit of the bank. The dimensions of the cells making up the purification circuit are such that the exchange of materials or their regeneration in the case of saturation will only be necessary one time a year.

(f) Safety in the case of an explosion

In case of explosion of a pressure tube, the tube of the gaseous bank having very little inertia simply guided to the low part is deformed or crushed without the incident leading to grave risks.

If, moreover, one admitted that the tube might be lacerated, the moderating water pouring in there at the rate of about 20 meters per second would compress the gas. It would result in a liberation of 100 pcm of reactivity. However, in the same time there would be an ejection of 2.8 cubic meters per second of moderator from the vessel. This effect largely compensates the danger which would be presented were it by a rupture of a gaseous bank.

7. Experimental confirmation

(a) Justification of experiments

The experiment constitutes at first the realization of a prototype of gaseous bank and permits the establishment at this point of the criteria of fabrication both with respect to the severe conditions of leaktightness of the system and the confirmation of calculated performances. It permits the establishment of the rules for development.

Then operational tests in emptying or in refilling carried out beginning with well determined conditions fix the exact dimensions of the orifices to be placed in the circuits.

Finally, the experimental model is subjected to endurance tests which are planned to guarantee the quality of the different components of the circuit and the effectiveness of the enclosed solutions.

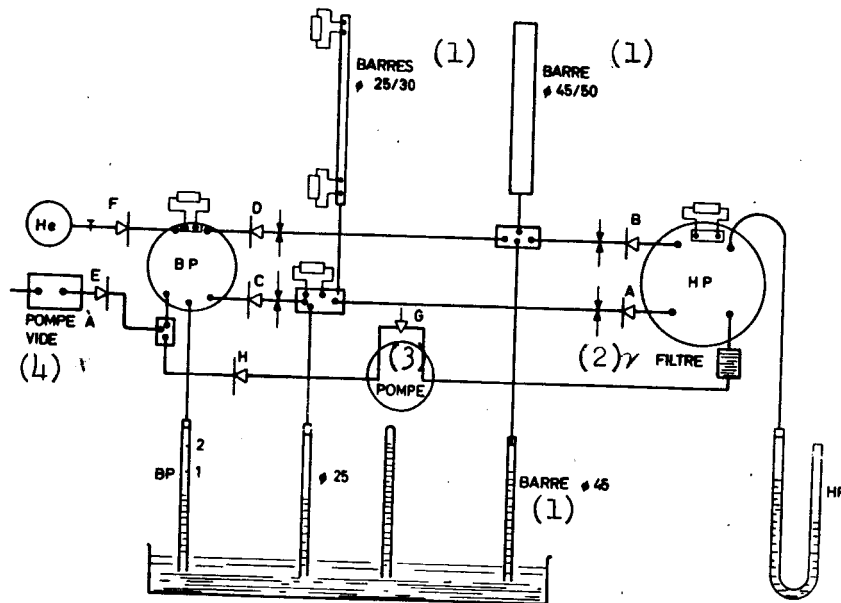


Figure 12

Schematic of the Test of Gaseous Banks

Key: 1 - bank
 2 - filter
 3 - pump
 4 - vacuum pump

(b) Experimental test (fig. 12)

The maximum pressure of the high pressure reservoir is slightly above atmospheric pressure. For a volume of 13.5 liters, its pressure is somewhere between 0.7 bars and 1.47 bars.

A higher pressure than this, besides the risks of leakage, risk impeding the operation of the pump, a lower value of pressure would lead to too large a volume of the high pressure reservoir and result in an additional investment of helium 3.

The low pressure reservoir has a capacity of 10 liters and its lowest pressure is 0.02 bars. A compensation or shim bank is made up of a tube having an internal diameter of 25 millimeters and a length of 4.5 meters. The pressure in the bank varies between 0.025 and 0.64 bars. The three other banks are represented by a single tube of which the inside diameter is 43 millimeters.

Each bank is connected to the low and high pressure reservoirs by two electric valves discharging each one through an orifice. This arrangement permits the validity of the chosen solution by operating on one bank, on a group of three banks, or on the equivalent on a group of four banks. The electric valves are normally closed. The regulation of the amount of time that an electric valve remains open permits the recording the variation of the pressure of the considered assembly.

The control of the amount of time remaining open is effected by means of a relay containing two concentric windings. The delay is regulatable between 0.3 and 3 seconds.

The measurement of the pressures is made with the help of static manometers made up of simple barometric mercury tubes in the amount of:

- 1 on each high and low pressure reservoir
- 1 on each bank
- 1 standard barometer

The differential manometers to the membranes are arranged as follows:

- 1 on each reservoir
- 3 on each of the banks

An oscillographic recorder permits the simultaneous reading of three data points. The starting and stopping of the pump are controlled by the pressure which exists in the low pressure reservoir with the help of contacts placed on the column of mercury.

A damper valve is located between the pump and the low pressure reservoir. It operates when the pump is stopped. It prevents the operation of the pump as a receiver when it is stopped. A filter at the outlet of the pump returns the dust particles and droplets of oil. The pump is of the type CGR model Zephyr 5 single stage with a supply of 5 cubic meters per hour under a vacuum of the order of 10 mm of mercury (limiting vacuum 2×10^{-3} mm of mercury). The power of its motor is 1/3 CV.

A special pump is necessary in order to make the vacuum in the circuit. The tests are conducted with the gas natural helium.

It should be noted that the length of the connecting tubes are representative of those which will exist in pile.

(c) Results of the tests on the experimental rig (fig. 13)

The tests give the assurance that the principle of control used is valid by a measure of the rapidity of the system on emptying and on refilling. In effect, a first series of tests consisted of measuring the increase of pressure in the bank during the passage of the helium from the high pressure reservoir to the banks as a function of the amount of time that the valve was held open. The objective aimed for is to obtain an incremental increase of pressure of 15 millimeters of mercury corresponding to an assigned control worth of 25 pcm. It is proven that the amount of time that a valve is held open varies slowly at high values of high pressure.

TIME OF REFILLING OR EMPTYING FOR 25 PCM

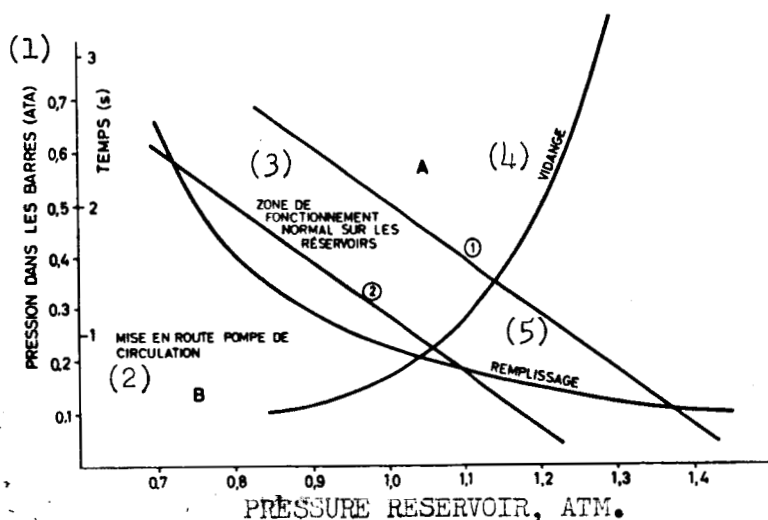


Figure 13. Pressure in the Banks as a Function of the Pressure in the High Pressure Reservoir

- Key: 1 - pressure in the banks (abs. atm.)
 2 - circulation pump put into operation
 3 - normal reservoir functioning zone
 4 - discharge
 5 - re-fill

The same measurements have been carried out for the draining from banks at the maximum pressure for the low pressure reservoir and the minimum pressure in the banks. They permit the equal verification of excellent performances due to the rapidity of the wave transmission of pressure in the helium (fig. 14).

The orifices placed at the exit from the high pressure valves measure, respectively, 0.5 mm and 0.86 mm; the orifices placed at the entrance to the low pressure valves are, respectively, 0.7 mm and 1.22 mm for the banks of diameters 25 mm and 43 mm.

For safety operation, different orifices are tried and permit determination of the correct cross section for the introduction of 400 pcm in 0.1 seconds (fig. 15).

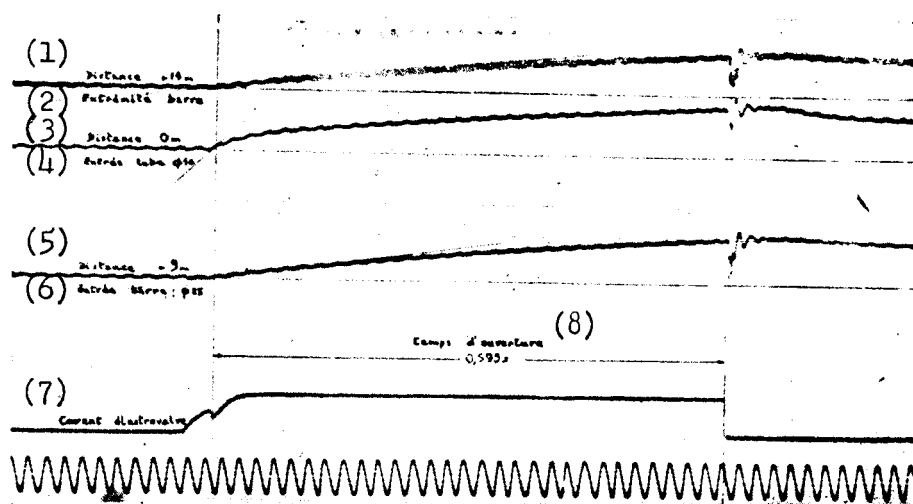


Fig. 14.

Step No. 2

High pressure:

1.410 to 1.386 atm.

Bank pressure:

0.045 to 0.70 atm.

Key: 1 - distance
2 - end of bank
3 - distance
4 - inlet tube
5 - distance
6 - inlet of bank
7 - electric valve current
8 - orifice time

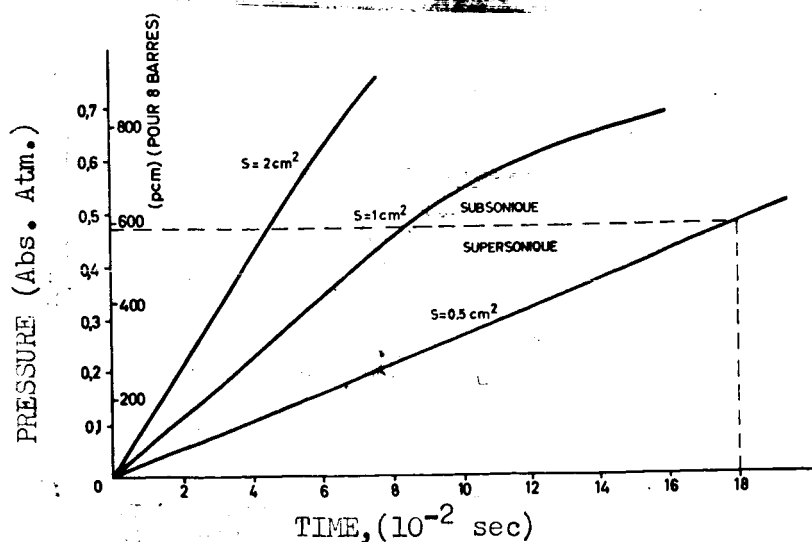


Figure 15. Refilling of the Security Banks

Key: 1 - (PCM) (for 8 banks)
2 - subsonic
3 - supersonic

8. Construction

On the pieces of equipment themselves, the joints have been reduced as much as possible; hence, the electric valves are of the inert gas-welded type. The manual fork valves to seal off the blower and the apparatus of measurement without exception is sealed from the exterior by welding around the edges. The maximum value of tolerable leaks are, in these conditions, less than 2×10^{-5} lusec per piece of apparatus. (My guess is that "lusec" is microliters per second.) }

The most delicate subassembly from the point of view of gas leakage is the pump. A study of blower pumps has been conducted during the course of the preliminary investigations. Taking into account the difficulties encountered and the planning of the construction, the solution is rejected. The pump finally selected is a paddle pump developed by SAEMA for use in circuits of helium. The contractor guarantees a gastightness of 10^{-4} lusec } with respect to the exterior.

It is necessary to maintain the amount of oil in the circuit at a very low value for the following reasons:

- (a) Under a neutron flux, the oil polymerizes leading to a fouling of the circuit. The presence of oil would lead to a fouling of the circuit for the purification of tritium. Furthermore, this presence would limit the efficiency of the purification system by formation of a film of oil on the reagents making them more inaccessible to the tritium and to the hydrogen. Furthermore, the tritium would be able to substitute partially by isotopic exchange with the hydrogen in the molecules of oil.
- (b) One of the conditions essential to gastightness up and downstream of the electric valves and the stopcocks is that they must function in a perfectly clean circuit. It is therefore necessary on one hand to connect to the pump a high efficiency filter in order to recover the oil emulsions; and on the other hand, to use an oil with a very low vapor pressure. The SAEMA pump satisfies these conditions. Gastightness up and downstream is fixed at:

0.1 lusec for the electric valve pumps
 2×10^{-5} lusec for the isolating stopcocks

In order to assure that all these conditions are respected, even after a reasonably long period of operation, and in order to keep only that material of which the endurance is perfectly proven, some experimental banks have been developed in the hope of guiding the selection of materials. Without going into the detail of these experimental banks, let us note that it demands for example a million maneuvers with the electric valves without failure and while maintaining the guarantees of gastightness and 5,000 maneuvers of the stopcocks of isolation under the same conditions.

Requirements connected to the fundamental condition of the conservation of gastightness when disassembling and the exclusion of false maneuvers.

The particular example of figure 16 describes the actual solution designed to prevent the effects of false maneuvers during repairs. The No. 1 tritium purification circuit connected to the circuit by the junctions R10 and R11 is bracketed by the electric valves E17 and E18. It is, furthermore, connected to the vacuum pump to the electric valve E33.

The connections R10 and R11 contain a microcircuit breaker. The accidental or voluntary loosening of one of these connections results in the triggering of the microcircuit breaker which cuts the current on EV17, 18 and 33, entirely isolating the circuit. The loss of helium 3 is, in this case, limited to the volume contained between these 3 electric valves.

This choice leads to an increase in the number of electric valves on the circuit and, as a consequence, to a considerable loading of the necessary electrical circuitry. It seems, however, justified with respect to a considerable financial loss which would result from an accidental leakage of the circuit due to someone ignoring the rules for disassembly in the case where the electric valves were replaced by simple manual stop-cocks. When all the tests of the elementary components have been effected, an experiment representing the circuit complete with the definite components will be realized. This model or test will start to operate at the beginning of the year 1964. Some operational tests and prolonged tests of endurance are planned during the course of the first semester of 1964 before going on to the definite design.

(a) Construction

It has been contracted to the Atomic Alsatian Atlantic Group and includes the principal subassemblies:

- material located on the reactor block
- pneumatic circuits for adding to the banks
- electric material for control and command

It corresponds to the general schematic of figure 16.

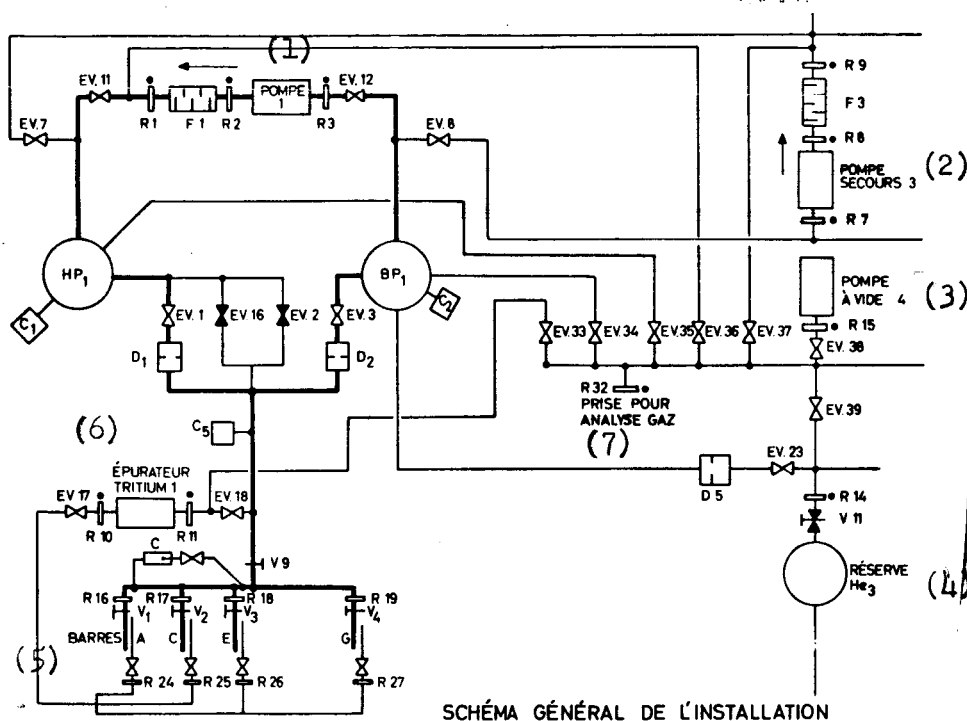


Figure 16. General Schematic of the Installation

- Key:
- 1 - pump 1
 - 2 - standby pump
 - 3 - vacuum pump
 - 4 - He_3 reserve
 - 5 - banks
 - 6 - tritium 1 purification unit
 - 7 - stopcock for gas analysis

Figure 16

General schematic of the installation.

The material situated on the reactor block is made up of the tube of the gaseous bank constructed of Zircaloy 2 in order to prevent the residual control worth passing 50 pcm for 8 banks. For reasons of mechanical strength, it is necessary to carry its internal diameter to 25 mm with a wall thickness of 2 mm. It has a length of 4.5 meters. Fixed at the top in the biological shield it is simply resting on the bottom in an integral funnel of the vessel. It extends up to the head of the bank by a tube of stainless steel of a diameter of 14x16 mm. Inside the radiation shield the tube is curved in order to presently direct leakage of radiation. The Zircaloy-stainless steel connection is brazed with a silver-aluminum alloy.

A slender tube of diameter 4x6 coaxial with the preceding one leaving a particular connection on the head of the bank descends down to the height of the Zircaloy. It assures the transfer of the drawn-off gas up to the purification cell. This assembly is carried by a tube guide whose dimensions are the same as those which carry the fine control banks, thus interchangeability is assured. The bank and biological shield assembly is placed in the corresponding shaft leaving a region in which a part of the moderator flow circulates in an upward direction. The outflow takes place at the base of the head of the bank. A thermostatic probe permits the control of the effective cooling and, if it is necessary, to adjust the flow. The problem of cooling is helped by the use of the helium 3 which does not sensibly absorb gamma radiation and in which neutronic absorption does not produce a notable local heat release.

There are two pneumatic circuits for addition to the banks. They permit the introduction of helium 3 in each of the two groups of four banks, or to remove it, following orders that it receives.

Each of these circuits consist of:

- 1 high pressure reservoir of 20.5 liters
- 1 low pressure reservoir of 18 liters
- 1 pumping system supplying 25 cubic meters per hour
 - of which the intake pressure is between 0.006 and 0.05 bars and the outlet pressure is between 0.6 and 1.4 bars
- 1 filter placed at the outlet preventing the transfer of oil into the circuit
- 1 series of electric valves permitting all the movements of gas toward the banks in normal operation
- A series of electric valves for isolation assuring the security of the circuit in the case of disassembly.
- Some manual stopcocks for isolation permitting the suspension of the use of certain parts of the circuit.

A tritium purification cell with its circulation blower, the catalytic furnace, the refrigerator, the dryer of the molecular screen and the filter.

The total capacity of the purification circuit is sufficient for one year of service at the nominal control strength of the system of control banks. The supply of gas treated is 10 liters per hour.

The system is supplied with auxiliary circuits consisting of:

- 1 standby pumping system
- 1 classical vacuum pump of which the flow rate is about 2.5 cubic meters per hour permitting the creation of a vacuum in a circuit before the introduction of helium 3
- 1 system for introducing the helium containing simultaneously the reserve of new gas.

All the circuits are constructed of stainless steel. The tubing is made up of tubes 10X12 mm in diameter. [NOTE: I think at this point the 10X12 mm in diameter means I.D. of 10 and O.D. of 12.*] The orifices are made up of nozzles of the Solex type. Each of the groups is mounted on a framework and placed in a room near to the banks.

(b) Tests

Tests of the elementary components: These are carried out in the first place on the measures of the gastightness with respect to the exterior of the same upstream and downstream of all the elements.

Tests of response times of electric valves and tests of endurance of the mechanical components, pumps, and electric valves are assured. In the same manner, tests on the subassemblies made up of elements separated from the circuit (volumes, pump, etc.).

Tests on the assembly of the material: They are composed principally of the following:

- verification of the leaktightness of all the elements assembled
- tests on the operation on the compensation circuits: refilling, emptying.
- tests on the safety operation
- tests on the operation of the purification cell
- verification of the backup system
- verification of additional systems
- verification of the auxiliary vacuum pump
- tests on the overall gastightness.

9. Use of gaseous compensation banks

(a) Principles of reactor control

In normal operation:

The fine control banks are in service at all levels of power.

The safety banks withdraw from the core at powers above 175 MW.

* TRANSLATOR'S NOTE

The compensation banks come into service when all of the safety banks are in the raised position.

The overall safety of the reactor is assured by always saving in a raised position one or two banks of safety even at low levels of neutron power.

The servomechanisms of the fine control banks receive position orders. Their effectiveness being limited, it is expedient to send orders to other means of control when the fine control banks tend to approach either end of their range. Therefore, they react in conjunction with the safety banks at startup and with the compensation banks during the increase in power. A selector permits the choice between one group and two groups of compensation banks.

A possibility of manual control of the compensation banks is offered to the operator. A safety lock prohibits at that time all action on the safety banks. This control is able to be applied on one bank or a group of banks. It may take place for regulation or for safety.

The compensation banks play an effective control at the time of a too rapid increase of power after a prolonged operation at an intermediate level by carrying into the core a large reactivity worth. The duration of this transient prohibits the use of black banks.

(b) Interaction between the fine control banks and the compensation banks (fig. 17)

In order to preserve the total efficiency of the fine control banks, it is desirable that the maximum range of position around the equilibrium position be also reduced whenever possible and correspond approximately to a quarter of the total range of the fine control banks.

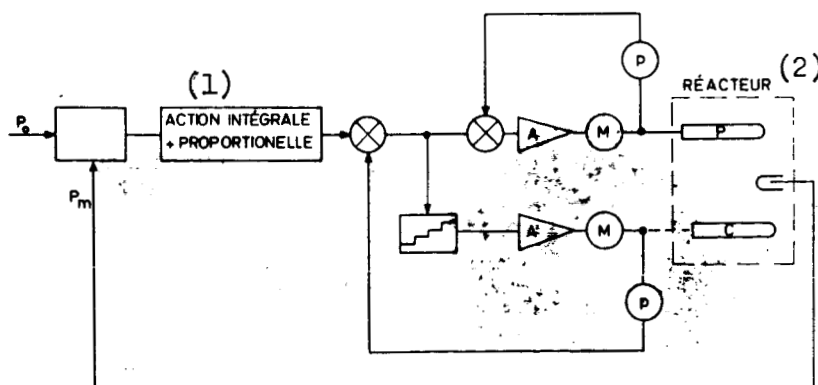


Figure 17. Scheme of Interaction Between Compensation Banks and the Fine Control Banks

Key: 1 - integral and proportional action
2 - reactor

The reactivity range of the banks being about 100 pcm, the maximum desirable range is, therefore, about 25 pcm. That is to say, if the banks differ from the equilibrium position beyond the allowable threshold the regulation system compensates in such a way as to place the fine control banks back in their maximum effective area of operation. The speed of variation of the compensation banks, during their displacement at the same time as the fine control, should be such that the fine control banks are able to effect the inverse movement. That is to say that an exchange of 25 pcm should be accomplished at the maximum instantaneous speed of 30 pcm per second.

(c) Shutdowns

In case of an incident, each bank should be able to be removed from its channel. For that, the manual valves permit the isolation of the bank from the principal circuit and the disconnection of the gas collectors. It would be manipulated by using a hood which would cover the outlet of the channel and which would be under a helium atmosphere in order to prevent the pollution of the heavy water.

Each simple component susceptible to engine failure such as the pumps or to saturation such as the tritium purification cell and the oil filter, will be able to be isolated from the general circuit, the system being then started again with the spare. Shutdown for the purpose of repairing or exchanging these elements is easy since they are contained in a chamber placed in a room reserved for this purpose and therefore easily accessible.

C. ECONOMIC CONSIDERATIONS

The actual state of the studies on the gaseous bank for EL4 permits the preparation of a comparison of prices between classical solutions (mechanical banks) and this new solution.

There appears a priori at the level of the advanced design a net economy in favor of the gaseous bank. However, it is well to postpone until later the analysis of a particular case before making a definite conclusion.

TABLE II
COMPARATIVE PRICES OF A MECHANICAL BANK
AND OF A GASEOUS BANK*

Banks of mechanical fine control (8)	
1 Studies	8.22
Tests and installations of tests	16.15
2 So-called banks and tubular structures	4.72
Mechanism of control	23.2
Electrical equipment	17.2
3 Construction and on-site testing	16.3
4 Spare parts	7.6
Banks of gaseous compensation (8)	
1 Studies	12.55
Tests and installations of tests	15.70
2 Tubular structures and connecting tubing	1.83
Pumping system	13.17
Electrical equipment	17.6
3 Construction and on-site testing	21.9
4 Investment in helium-3	7.2
5 Spare parts (including extra helium-3)	10.05

* Bases of estimation - Design of EL4 for:

- 8 banks of compensation gases (850 pcm)
- 8 banks of mechanical fine control (700 pcm)

The value 100 is given to the system of the gaseous bank.

Tables II and III reproduce the partial comparative prices in the case of EL₄ with the bank of mechanical fine control and the bank of gaseous compensation. We have calculated these prices with a common base: 8 banks of each type effectively comparable elsewhere. The different prices are indicated by fixing at 100 the total value of the gaseous bank.

TABLE III
COMPARISON BETWEEN ONE BANK OF MECHANICAL FINE
CONTROL AND ONE BANK OF GASEOUS COMPENSATION

	Mechanical fabrication	Electrical mechanisms	Price 1+2+3	Total price for one bank 1+2+3+4+5
Fine control bank (P)	3.5	5.65	10.7	11.6
Compensation bank (C)	1.91	4.12	10.4	12.5
$\frac{P-C}{C}$	~84%	~37%	~3%	~ -7%

These tables lead to the following remarks:

1. The financial comparison of strictly mechanical equipment (structures, tubing, ~~pumping group for the~~ gaseous bank, the bank structure and control mechanism for the fine control bank) apparently lead to a net advantage of the gaseous bank.
2. It is necessary to add to this base price the necessary investment in helium 3. The actual state of the project permits the fixing contractually at 60 liters TPN the quantity of helium contained in the circuit of the banks. (NOTE: TPN probably stands for Normal Temperature Pressure.) This would lead to taking into account the actual price of the helium 3, an investment for the bank in the order of 6,000 francs.

The price of fabrication and initial investment allows an advantage of about 25 percent to the profit of the gaseous bank.

3. But the price of the electric part of the gaseous bank is heavily burdened in the case of EL₄ for two reasons:

- because we have tried to obtain a total safety in case of disassembly with respect to leakage of helium 3 into the atmosphere. This is justified by the actual very high price of helium 3. The additional electrical equipment necessitated by this requirement represents approximately the price of one load of gas.

- with concern with the compatibility with the rest of the installation and for ease in handling of the entire system and in order to reduce the delays due to the triggering of electromagnetic relays, the system of electrical materials is transistorized. This solution, at the present time, and in this particular case, is more expensive than a solution which relies on classical electronics.

It is necessary, therefore, to note that the price of the design of the gaseous bank system would be able to be reduced, probably by a factor of 2 upon the future realizations following from:

- the probable reduction of the price of helium 3 in case of the development of the need for tritium especially; this would lead to a relaxation of the safety measures required for disassembly
 - the certain lowering in price of transistorized equipment in the years to come.
4. The prototype character and the requirements concerning maintainability and leaktightness of the gaseous bank circuit have led to the providing of significant provisions for the equipment relative to study and tests in the factory during construction and for tests on the site. This equipment will become notably less in the future designs while the equipment corresponding for mechanical banks is very difficult to reduce in size.
 5. Spare parts: We have included in the comparison of prices the first lot of spare parts which it seemed suitable to have in supply in order to prepare for possible failures of the material. Strictly from the mechanical and electrical viewpoint, the advantage of the system of gaseous banks seems clear. However, prudence requires that we include a complete charge of helium 3 in our spare supplies in order to prepare for a false maneuver, an accidental leak, or to compensate for the consumption of the absorbing gas.

The analysis thus made of the respective net prices of the two solutions makes it apparent that in the case of this first application (EL₁), and taking into account the safety factors that the two solutions are about equivalent (7% greater for the gaseous bank), but in the future applications in the case of the generalization of the solution using gaseous banks, the net price of gaseous banks will be considerably lower.

D. CONCLUSIONS

It is possible to use helium 3 in order to carry out the following functions with the help of a bank of gaseous control: (a) security, (b) compensation, and (c) fine control.

In the particular case of the reactor EL₁ which requires dynamic performances sufficiently high in fine control, it has been preferred to use mechanical banks of weak total effectiveness for fine control, taking into the planning which has already been fixed. There is nothing definite about this choice for the future and we think that it is possible to realize a

correct fine control using uniquely gaseous banks in the case of power reactors. In this first application many operations are required on the gaseous banks.

The original character of the solution described here is supplemented as the result of the use of helium 3 as the absorbing gas and the effective application of the system which has left the state of advanced design in order to be put into service on the EL₁. The actual technological difficulties which have often postponed the choice of the type of the solution are in the course of being resolved.

Without being able yet to fix as early as now a definite manner, the domains of action of this type of means of control with respect to the other means available, one is able in conclusion to report the distribution of the means of control on the reactor EL₁. }

Five means of control are anticipated:

- rearrangement of the fuel loading of the reactor and using absorbing elements.
- use of a salt of a strongly absorbing element in a dilute solution in the moderator.
- black banks of high effectiveness and with very modest dynamic performances.
- gray banks of low total effectiveness presenting dynamic performances which are good enough (passing a band in the linear domain 2Hz--limitation of the speed to 30 millipercent per second).
- gaseous banks

These different means are foreseen for application as follows:

- rearrangement of fuel: compensation of the variations in reactivity due to the burnup of the fuel. This compensation would not be able to be accomplished in a continuous fashion. Between two rearrangements, the compensation is carried out by the gaseous banks.
- soluble poison: compensation of the excess reactivity between the beginning of clean power and a loss after about 48 hours due to the delay in the buildup of xenon with respect to the buildup in power. This solution permits taking over the compensation of the xenon effect very rapidly without provoking the distortion and flux such as would be found in the presence of black banks in the core. The variations of xenon poisoning due to changes in power are compensated by the gaseous banks within the limit of the disposable reactivity.
- black rods or banks: these banks serve uniquely in the compensation of variations in reactivity between the cold state and the hot state

and for safety rods. These banks are therefore constantly outside the reactor during operation at power.

- gray mechanical banks: these banks serve as the fine control of the reactor; they are capable of being controlled so accurately that the position of the banks in the reactor is practically fixed at steady state (no axial distortion of flux in the reactor). The variations in reactivity called for by the fine control are assured by these banks in the limits of approximately ± 25 pcm, larger variations are supplied by the gaseous banks. The small total worth of these banks permits the prediction of excellent dynamic performance without endangering the safety of the reactor.
- gaseous banks: these banks have, in effect, many functions. They supply backup for the fine control banks for large-size variations in power due to commands or to accidents. They assure equally the compensation for variation of the xenon effect and temperature during changes in power level and the compensation for fuel burnup between two fuel reloadings. Applied to the safety function, they permit the very rapid introduction of a limited control worth sufficient to shut down the reactor without distorting the flux, therefore without local temperature excursions on the tubes in the case of an accident.

The combination with the classical means of control by mechanical absorbing elements with two new means of chemical control (soluble poison and gaseous bank) present an acceptable solution to the problems of control of thermal nuclear reactors with typical power levels (specifically high powers, with temperatures near the limits of technology).

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